Spin Polarization Dependence of the Coulomb Drag at Large r_s

R. Pillarisetty,[1] Hwayong Noh,[1,2] E. Tutuc,[1] E.P. De Poortere,[1] D.C. Tsui,[1] and M. Shayegan[1]

[1]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544*
[2]*Department of Physics, Sejong University, Seoul 143-747, Korea*

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We find that the temperature dependence of the drag resistivity (ρ_D) between two dilute two-dimensional hole systems exhibits an unusual dependence upon spin polarization. Near the apparent metal-insulator transition, the temperature dependence of the drag, given by T^α, weakens with the application of a parallel magnetic field ($B_{||}$), with α saturating at half its zero field value for $B_{||} > B^*$, where B^* is the polarization field. Furthermore, we find that α is roughly 2 at the parallel field induced metal-insulator transition, and that the temperature dependence of ρ_D/T^2 at different $B_{||}$ looks strikingly similar to that found in the single layer resistivity. In contrast, at higher densities, far from the zero field transition, the temperature dependence of the drag is roughly independent of spin polarization, with α remaining close to 2, as expected from a simple Fermi liquid picture.

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The spin degree of freedom of the electron plays a fundamental role in condensed matter physics, and significantly influences the electronic properties of solids. For simple metals, which are well described by Fermi liquid theory, the role spin plays in electron transport is reasonably well understood. In contrast, the spin degree of freedom plays a unique role in stabilizing several exotic non-Fermi liquid states, such as BCS superconductivity[1]. Recently, much attention has focused upon dilute two-dimensional (2D) systems and the possibility that the spin degree of freedom stabilizes a novel phase of matter. These systems, which have large ratios of carrier interaction energy to kinetic energy ($r_s > 10$), exhibit an anomalous metallic behavior and an apparent metal-insulator transition (MIT)[2], contradictory to the scaling theory of localization[3]. Despite numerous studies, no conclusive understanding of the behavior in this regime exists. However, many believe that the spin degree of freedom plays an important role in stabilizing the metallic behavior. This results from numerous observations[2, 4, 5] that the metalliclike behavior is suppressed as the 2D system is spin polarized by the application of a parallel magnetic field ($B_{||}$). Furthermore, recent experiments, in a variety of different systems[6, 7, 8, 9, 10], show a strong enhancement of the spin susceptibility as the carrier density is reduced near the MIT, suggesting a possible transition to a ferromagnetic ground state. To help elucidate the bizarre role spin plays in dilute 2D systems, we have studied the spin polarization dependence of the Coulomb drag near the 2D MIT.

Drag resistivity measurements [11] between parallel 2D layers provide a powerful probe of carrier-carrier interactions. These experiments are performed by driving a current (I) in one layer, and measuring the potential (V_D), which arises in the other layer due to momentum transfer. The drag resistivity (ρ_D), given by V_D/I, is directly proportional to the interlayer carrier-carrier scattering rate. In a Fermi liquid picture, the drag should follow a T^2 dependence at low temperatures[12]. Furthermore, the Fermi liquid framework implies that the temperature dependence of the drag should remain independent of spin polarization. While well understood exceptions to the T^2 dependence exist[13], measurements of the drag at $B_{||} = 0$, near the apparent 2D MIT, exhibit an anomalous T dependence, which is greater than T^2 and correlated with the metalliclike T dependence in the single layer resistivity[14].

In this article, we study the effect of spin polarization on the temperature dependence of the drag between dilute 2D hole systems. Near the apparent MIT, we find that the temperature dependence of the drag, given by T^α, weakens significantly with the application of $B_{||}$, with α saturating at half its zero field value above the polarization field (B^*). Furthermore, we find that α is roughly 2 at the parallel field induced MIT, and that the T dependence of ρ_D/T^2 at different $B_{||}$ looks strikingly similar to that found in the single layer resistivity. In contrast, at higher densities, far from the zero field MIT, the T dependence of the drag is roughly independent of spin polarization, with α remaining close to 2, as expected from a simple Fermi liquid picture.

Two samples were used in this study. Sample A (B) contains a double quantum well structure, consisting of two 150 (175) Å Si doped p-type GaAs quantum wells separated by a pure 150 (100) Å AlAs barrier, which was grown by molecular beam epitaxy on a (311)A GaAs substrate. Sample A (B) has an average grown layer density and center to center layer separation of 2.5 (7.0)$\times 10^{10}$ cm^{-2} and 300 (275) Å, respectively. The average mobilities in each layer of Sample A (B) at 300 mK, are 1.5 (6.7)$\times 10^5$ cm^2/Vs. Single layer transport in Sample A (see [14]) shows a clear zero field MIT at $p = 8.5 \times 10^9$ cm^{-2}. The samples were processed allowing independent contact to each of the two layers, using a selective depletion scheme[15]. In addition, both layer densities are

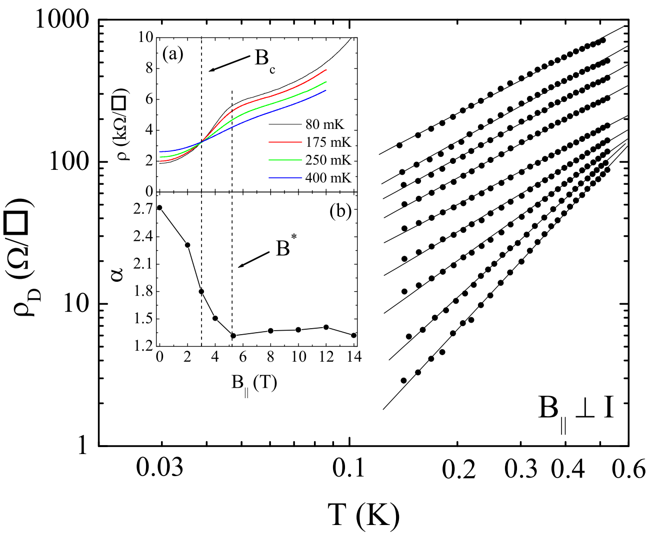

FIG. 1: ρ_D vs T on log-log scale at $p_m = 2.15 \times 10^{10}$ cm^{-2}, with $B_{||} \perp I$. Traces are for (from bottom) $B_{||} = 0$, 2, 3, 4, 5.3, 8, 10, 12, and 14 T. Solid lines are the best linear fits of each trace. Inset (a): ρ vs $B_{||}$ for different T. Inset (b): α vs $B_{||}$. α deduced from the slope of the linear fits in the main plot. $B_c = 3$ T and $B^* = 5.3$ T indicated by the dashed lines.

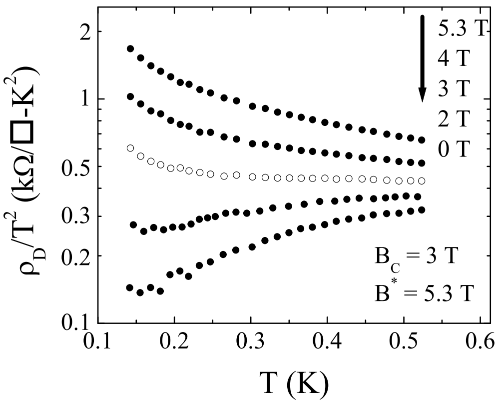

FIG. 2: ρ_D/T^2 vs T for (from bottom) $B_{||} = 0$, 2, 3, 4, and 5.3 T. $p_m = 2.15 \times 10^{10}$ cm^{-2}, with $B_{||} \perp I$. Data at $B_{||} = B_c$ shown as open circles.

independently tunable using evaporated metallic gates.

The data presented in this paper were obtained in top loading dilution and ^{3}He refrigerators. The densities in each layer were determined by independently measuring Shubnikov-de Haas oscillations. Drive currents between 50 pA to 10 nA were passed, in the [$\bar{2}$33] direction, through one of the layers, while the drag signal was measured in the other layer, using lock-in techniques. To ensure no spurious sources contributed to our signal, all the standard consistency checks associated with the drag technique were performed[11].

We begin our presentation of the data by first looking at the temperature dependence of the drag at different $B_{||}$. This is presented in Fig 1 where we plot ρ_D vs T on log-log scale, for matched layer densities (p_m) of 2.15×10^{10} cm^{-2}. Here $B_{||}$ is aligned perpendicular to the drive current. At this density, the single layer resistivity exhibits a strong metalliclike T dependence at zero field, and earlier studies show that ρ_D exhibits an anomalously large enhancement with $B_{||}$[16]. Single layer magnetotransport, shown in inset (a), exhibits a clear $B_{||}$ induced MIT at $B_c = 3$ T, and the onset of full spin polarization at $B^* = 5.3$ T. The data in the main plot clearly shows that the T dependence of the drag has an unusual dependence on $B_{||}$. At low fields, the slopes of the linear fits of the data weaken significantly as $B_{||}$ is increased. In contrast, at higher $B_{||}$, the slopes of these fits seem to be independent of increasing $B_{||}$. To examine this more carefully, we plot the slopes of each of these fits against $B_{||}$ in inset (b). Here the slope corresponds to the exponent, α, where $\rho_D \propto T^\alpha$. At zero field, α is significantly larger than 2, as has been discussed earlier[14]. From this plot it is clear that as $B_{||}$ is increased, α weakens significantly, and then saturates for $B_{||} > B^*$. In addition to this observation, there are two other very interesting features to this plot. First, the value of α for $B_{||} > B^*$ is roughly half that found at zero field. Secondly, α is close to 2 (about 1.8) when $B_{||} = B_c$. To show this more explicitly, in Fig 2 we plot ρ_D/T^2 vs T, for $B_{||} = 0$, 2, 3, 4, and 5.3 T. The first point we make is that this data looks strikingly similar to a plot of the T dependence of the single layer resistivity at different $B_{||}$. Furthermore, ρ_D/T^2 changes from increasing with T to decreasing with T very close to $B_c = 3$ T, where the parallel field induced MIT is observed in the single layer resistivity.

Although it surely appears that these observations, primarily the saturation of the T dependence above B^*, are due to a spin effect, one must be careful to consider orbital effects[17]. Due to the finite layer thickness of our 2D systems, the coupling of $B_{||}$ to the orbital motion of the carriers, can significantly effect the in-plane magnetotransport. The high field magnetoresistance observed for $B_{||} > B^*$ in 2D GaAs samples[5, 9], is typically believed to arise from such an orbital effect. By reorienting $B_{||}$ such that it is parallel to the drive current, the contribution of orbital effects to the in-plane magnetoresistance can be significantly reduced, as compared to when $B_{||} \perp I$[17]. This is shown in inset (a) of Fig 3, where we plot the single layer magnetoresistance for $p_m = 1.85 \times 10^{10}$ cm^{-2} with $B_{||} \parallel I$, at different T. It is clear that the high field magnetoresistance arising from orbital effects is much weaker in the $B_{||} \parallel I$ configuration. The data at $p_m = 1.85 \times 10^{10}$ cm^{-2} with $B_{||} \parallel I$ also shows a clear $B_{||}$ induced MIT at $B_c = 1.7$ T, along with a clear shoulder in the magnetoresistance, corresponding to full spin polarization, at $B^* = 3.4$ T. In the main plot of Fig 3, we present the T dependence

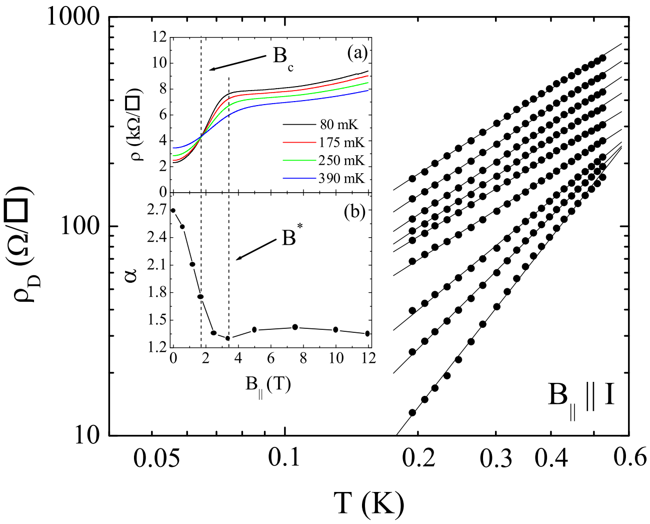

FIG. 3: ρ_D vs T on log-log scale at $p_m = 1.85 \times 10^{10}$ cm^{-2} with $B_{||} \parallel I$. Traces are for (from bottom) $B_{||} = 0$, 1.2, 1.7, 2.5, 3.4, 5, 7.5, 10, and 12 T. Solid lines are the best linear fit of each trace. Inset (a): ρ vs $B_{||}$ for different T. Inset (b): α vs $B_{||}$. $B_c = 1.7$ T and $B^* = 3.4$ T indicated by the dashed lines.

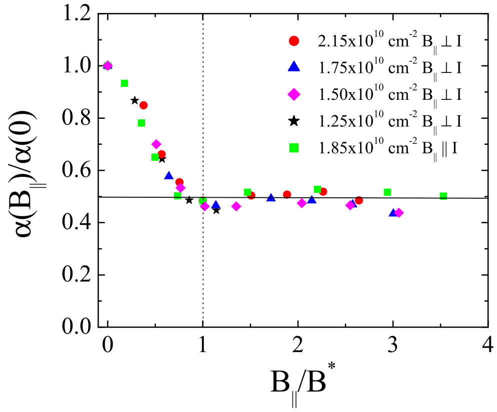

FIG. 4: $\alpha(B_{||})/\alpha(0)$ vs $B_{||}/B^*$ for $p_m = 2.15$, 1.75, 1.5, and 1.25×10^{10} cm^{-2}, with $B_{||} \perp I$ and for $p_m = 1.85\times10^{10}$ cm^{-2}, with $B_{||} \parallel I$.

of ρ_D at different $B_{||}$ for $p_m = 1.85 \times 10^{10}$ cm^{-2} with $B_{||} \parallel I$. Note here that the exact same behavior as seen with $B_{||} \perp I$ is observed, with the strength of the T dependence weakening as $B_{||}$ is increased and then saturating above B^*. To show this more explicitly, we plot α vs $B_{||}$ in inset (b). Again, α is found to saturate at roughly half its zero field value for $B_{||} > B^*$. In addition, α becomes roughly 2 (again about 1.8) at $B_{||} = B_c$. This data unambiguously shows that orbital effects are not playing a role here, and that the unusual behavior we observe arises from a spin effect.

To demonstrate the universality of this effect at low densities, near the apparent MIT, we plot all of our T dependence data taken for $p_m = 2.15$, 1.75, 1.5, and 1.25×10^{10} cm^{-2} with $B_{||} \perp I$ and for $p_m = 1.85 \times 10^{10}$ cm^{-2} with $B_{||} \parallel I$ on a scaled plot, which is presented in Fig 4. Here we plot α normalized by its zero field value against $B_{||}/B^*$ for each data set. These data sets range from $r_s = 9.2$ to 12.1, using $m^* = 0.17m_e$. As is shown in the plot, it is clear that all five of these data sets collapse onto each other. In addition, for all the data it is clear that the α found at zero field decreases by a factor of roughly 2, at the polarization field, and saturates upon further increase of $B_{||}$.

It is not hard to imagine that this behavior we observe must be related to the large r_s value of our dilute 2D system. In the small r_s limit, where carrier-carrier interactions are weak, Fermi liquid theory dictates that the T dependence of the drag should be independent of spin polarization. To investigate whether the bizarre behavior found in the dilute regime is suppressed when we go to lower r_s, we have investigated a sample with $p_m = 7.0 \times 10^{10}$ cm^{-2} ($r_s = 5.1$), which is far from the zero field MIT. At this density, the zero field properties of the drag, including a nearly T^2 dependence, are reasonably well described by Boltzmann theory[12]. In inset (a) of Fig 5, we present the single layer in-plane magnetotransport in this sample, for different T. These measurements were done with $B_{||} \parallel I$, at $T = 0.3$, 0.6, 0.9, and 1.2 K. A clear crossing point is found at $B_{||} = 11.6$ T. In addition, this data clearly shows the start of the shoulder feature at the highest fields. Our estimates place B^* somewhere between 17.5 and 18 T, which would correspond to roughly 90 % polarization at $B_{||} = 16$ T. In the main plot of Fig 5, we present the T dependence of ρ_D at $p_m = 7.0 \times 10^{10}$ cm^{-2}, for $B_{||} = 0$, 10 and 16 T. It is clear that, to first order, there is little change to the nearly T^2 dependence found at zero field. The α's deduced from the linear fits of these data, which are shown in inset (b), give $\alpha = 1.9$, 1.9, and 1.7 at $B_{||} = 0$, 10, and 16 T, respectively. It appears that whatever produces the unusual effect observed at low densities plays a perturbative role here. Here α decreases by roughly a factor of 1.1 as $B_{||}$ approaches B^*, in contrast to the factor of 2 decrease found at lower densities close to the MIT.

We would now like to discuss these experimental results and the consequences they yield, with regards to the 2D MIT problem. The first piece of data we comment on is the striking similarity of the T dependence of ρ_D/T^2 at different $B_{||}$ with respect to that in the single layer resistivity, which is shown in Fig 2. In a Fermi liquid picture, one expects the drag to exhibit a T^2 dependence and the resistivity to remain relatively temperature independent. However, at zero field the T dependence of both ρ and ρ_D are anomalously enhanced with respect to what should be expected for both properties. Our data clearly

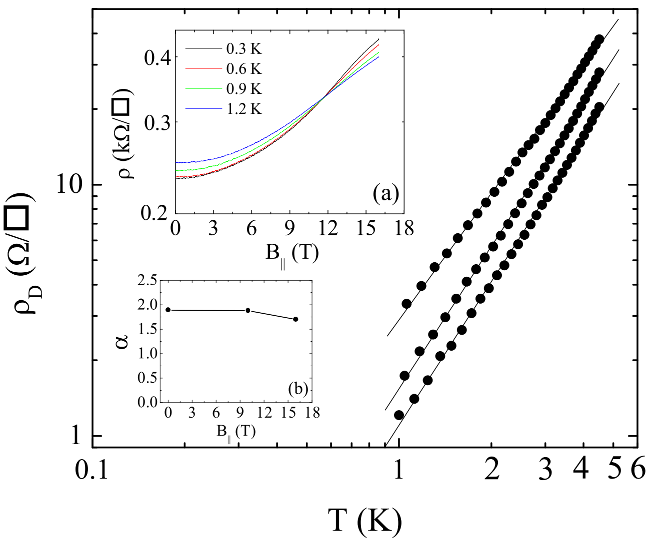

FIG. 5: ρ_D vs T on log-log scale, for $p_m = 7.0 \times 10^{10}$ cm^{-2}, with $B_{||} \parallel I$. Traces are for (from bottom) $B_{||} = 0$, 10, and 16 T. Solid lines are the best linear fit of each trace. Inset (a): ρ vs $B_{||}$, for $T = 0.3$, 0.6, 0.9, and 1.2 K. Inset (b): α vs $B_{||}$, deduced from the linear fits in the main plot.

show that the T dependence of both ρ and ρ_D exhibit exactly the same qualitative change as the 2D system is spin polarized, which is surprising since these are extremely different properties. This implies that there is some fundamental property in the system, which has a strong spin polarization dependence, which affects ρ and ρ_D in exactly the same way.

In general, the fact that the T dependence of the drag exhibits such a strong dependence on spin polarization, with α saturating at half its zero field value above the polarization field, seems to be a significant departure from Fermi liquid behavior. While we currently have no clear understanding of this bizarre behavior found in the dilute regime, we would like to comment on one possible explanation. Recently, a theory has been put forth, which states that the zero field MIT is a transition from a Fermi liquid to a Wigner crystal, via a series of intermediate phases[18]. In other words, near the transition, there is a phase coexistence of the Fermi liquid and Wigner solid. Due to the much larger spin entropy and spin susceptibility of the solid phase, free energy arguments dictate that the fraction of Wigner crystal in the 2D system (f_{WC}) will grow significantly with increasing temperature and spin polarization. This behavior is analogous to the Pomeranchuk effect in ^{3}He. Furthermore, the T dependence of f_{WC} weakens significantly as $B_{||}$ is applied, due to a reduction in the spin entropy of the system. For $B_{||} > B^*$, this T dependence saturates, since the spin entropy of the system is lost. This theory[18] states that the Wigner solid regions of the 2D system dominate the resitivity, and the underlying T and $B_{||}$ dependences of f_{WC} yield the metalliclike transport anomalies, which have been observed in numerous experiments[2]. An extension of this theory[19] shows that these Wigner crystal regions dominate the drag resistivity as well, and that the anomalies to the T and $B_{||}$ dependences of ρ_D similarly arise from the underlying T and $B_{||}$ dependences of f_{WC}. This could possibly explain why the T dependence of ρ and ρ_D/T^2 at different $B_{||}$ look so similar. Furthermore, our observation of a strong decrease in the strength of the T dependence of ρ_D as $B_{||}$ is increased, and its saturation for $B_{||} > B^*$ seem to directly follow from the fact that the T dependence of f_{WC} weakens as $B_{||}$ is applied, and saturates for $B_{||} > B^*$.

In conclusion, we have investigated the effect of spin polarization on the T dependence of the Coulomb drag near the MIT. We find that the temperature dependence of the drag, given by T^α, weakens as $B_{||}$ is applied, with α saturating at half its zero field value for $B_{||} > B^*$. In addition, the T dependence of ρ_D becomes roughly T^2 at the parallel field induced MIT. We find this effect to be independent of field orientation, ruling out the possibility that it arises from an orbital effect. Finally, at higher densities, far from the MIT, the T dependence of ρ_D is roughly independent of spin polarization, as expected from a simple Fermi liquid picture.

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